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THE MOST VIGOROUS SOUTH AUSTRALIAN TIDE

by C. SCHLUTER[*], J. A. T. BYE[†], & P. HARBISON[‡]

Summary

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Harmonic analysis of tidal records for the region between the city of Port Augusta and Yorkey Crossing in the upper Spencer Gulf indicates that the most vigorous South Australian tide probably occurs just north of the Whyalla Railway bridge and has a maximum range of about 4.1 m, just short of being classified as macrotidal. The special property of South Australian tides, that the semi-diurnal constituents (M_2 and S_2) have about equal amplitudes, results in very interesting shallow water tidal interactions, in particular the generation of a large amplitude quarter-diurnal constituent (MS_4). The intertidal environment of mangrove forests and especially the samphire flats of the upper Spencer Gulf is shown to be finely tuned to this shallow water tide.

KEY WORDS: tides, Spencer Gulf.

Introduction

The tides of South Australia have attracted interest for over 100 years (Chapman 1892; Easton 1970). However there appears to be no account of the region in which the largest tide occurs. This region is of interest to tidal theory because both Gulf St Vincent and Spencer Gulf have large semi-diurnal tides at their heads and also because the major lunar (M_2) and solar (S_2) constituents are of similar magnitude. The diurnal tide progresses from west to east along the Southern Shelf as a Kelvin wave which enters the South Australian sea where its amplitude and phase increase regularly and gradually towards the head of the gulfs. The semi-diurnal tide, on the other hand, displays a much more energetic response.

Tidal characteristics in Gulf St Vincent and Spencer Gulf

An almost progressive wave enters Investigator Strait and becomes converted into a standing oscillation within Gulf St Vincent (Bye 1976). Bowers & Lennon (1990) investigated the tidal character using the classical model (Bowden 1983) in which an incoming wave is reflected at the head of the gulf in the presence of a frictional force linearly proportional to the tidal current velocity. Particular attention was given to the importance of Backstairs Passage in this process. The system can be best described as a quarter-wave resonance of the open sea tide.

In Spencer Gulf the tidal resonance is more complex and lies closer to a three-quarter resonance in which a tidal node occurs between the head and the mouth of the gulf. This behaviour results in a minimum semi-diurnal tidal amplitude near Wallaroo, beyond which there is a rapid increase in amplitude towards the head of the gulf. Easton (1978) has given an elegant mathematical demonstration of this resonance which also uses a frictional term linearly proportional to the tidal current velocity. Numerical models of the tides of Spencer Gulf have been developed by Noye *et al.* (1981) and Bills and Noye (1986), including fine resolution models of tidal eddies in upper Spencer Gulf (Noye 1984; Noye *et al.*, 1994).

In both gulfs mangrove forest and samphire flats are extensive, especially near Port Wakefield, Port Adelaide[1] (Schluter 1993), Franklin Harbour and Port Augusta. The tides are of great ecological significance to these areas. The most vigorous tidal system in South Australia occurs between Port Augusta and Yorkey Crossing in upper Spencer Gulf. This distinctive region has the character of a brine estuary (Bye & Harbison 1990).

The action of tidal currents is responsible for internal mixing of the water column. Stabilising forces, such as surface heating and horizontal salinity gradients, tend to result in a stratified water column, the lower stratum being denser than the upper. The dynamics of the mixing process have been extensively studied, initially in temperature stratified environments such as the shallow European seas (Simpson & Bowers 1981), and more recently in the salinity stratified environment of the South Australian sea (Samarasinghe 1989). Stratification occurs when the ratio of the horizontal density gradient multiplied by the depth and

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[1] SCHLUTER, C. G. (1994) The Generation of Shallow Water Tides within a Mangrove Environment. MSc Thesis. The Flinders University of South Australia (unpubl.).

divided by the density and the root mean square of the slope of the water surface due to the tide exceeds a critical value (Bye 1990).

In upper Spencer Gulf the tidal currents maintain a vertically well mixed water column whereas in mid Spencer Gulf a very detailed and extensive observational programme has shown that transient stratification occurs (Nunes & Lennon 1987). At the mouth of Spencer Gulf the horizontal density gradient maintains a stratified exchange for about nine months of the year (Bye & Whitehead 1975; Lennon *et al.* 1987). In the summer months, however, the horizontal density gradient is reduced due to the reversal of sign in the temperature gradient and vertical mixing can also occur. These considerations highlight the significance of the tidal regime in the dispersion of dissolved material introduced into the water column in the coastal provinces of upper Spencer Gulf, especially in the brine estuary.

The Site

Previously, measurements of the tide in Spencer Gulf extended only as far north as Port Augusta. Recent tidal measurements (Bye & Harbison 1987, 1991, 1994) north of Port Augusta (Fig. 1), indicate that a very vigorous tidal regime exists. The site of the investigations was an old wooden bridge on which an abandoned mineral railway to a salt works crossed over Spencer Gulf. On the eastern shore of the gulf the salt bridge was originally connected with an embankment which cuts through the mangrove forest and into the samphire flats. The maximum span height of 4.4 m is just greater than high water springs, and at low water springs, the water is confined to a few central spans where the maximum depth is about 30 cm (Fig. 2a). The piers and spans are ideally suited for instrument deployments. Tide gauges were secured to the piers and current meters were suspended from the spans or mounted by poles driven into the ground. On the western side, beyond a narrower fringe of mangroves, the bridge leads directly to the salt works. The tidal observations undertaken at this site extended from 28 February to 28 March, 1986 (Bye & Harbison 1987).

Tide gauges and current meters were also deployed for shorter periods between the Central Australian Railway bridge and Yorkey Crossing. This station lies approximately 4 km further north of the salt bridge and is bordered on both sides by samphire flats (Fig. 2b) which are covered at high water springs and also during the rare floodings which originate on the Pirie-Torrens plains north of Yorkey Crossing (Bye & Harbison 1994).

Since the above observations were of limited time span, a second more extensive period was initiated in 1993. The choice and location of tidal equipment was based upon the pilot investigations. An Inter-Ocean S4 current meter was located within the town of Port Augusta at an abandoned road bridge using a cradle mooring device. The current meter is based upon an electromagnetic flux measurement and thus has no moving parts as do the conventional current meters. This makes the current meter immune to the effect of algal growth. The current meter obtained data between 27 July 1993 and 27 August 1993. A tide gauge located at this site proved faulty. The tidal constants in Table 1 were obtained from the Port Augusta power station tide gauge for the same period as the salt bridge deployment.

A bottom mounted pressure tide gauge was deployed at the Whyalla Railway bridge north of Port Augusta between 28 July and 30 October 1993. Another bottom mounted tide gauge was deployed at the salt bridge, but this gauge was destroyed by vandals. A bottom mounted tide gauge was deployed at the Central Australian Railway bridge between 18 September and 31 October 1993. This gauge clearly indicates the unusual tide of the region.

Tidal Analysis

To distinguish between a progressive and standing wave situation the phase differences between the tidal currents and elevations must be known. One of the most important aspects of tidal systems is the definition of standing and progressive waves. With standing waves, the phase difference between the tidal elevations and currents is 90° while for a progressive wave the phase difference is 0°. A standing wave may be considered as being the sum of two progressive waves, one directed landward and one of equal amplitude directed seaward. The landward energy flux associated with the incident wave is, in this case, balanced by the seaward energy flux of the reflected wave and thus there is no net energy flux. In dissipative situations the reflected wave will be frictionally attenuated and must be smaller in amplitude than the inbound wave and thus a perfect standing wave is impossible. As the tide propagates from the open ocean, various nonlinear distortions occur in the tidal signal. These distortions are primarily influenced by nonlinear mechanisms including frictional interactions and interactions with surrounding bathymetric features, as well as atmospheric effects and continuous freshwater discharges. The interactions of the primary astronomical tide discussed above may be represented by the growth of the shallow water tides which indicate the degree of nonlinear distortion of the primary signal.

In the analysis of tidal signals, it is common practice to decompose the tidal signal into a harmonic series of amplitudes and phases. The total tidal elevation or current may thus be represented by the sum of the

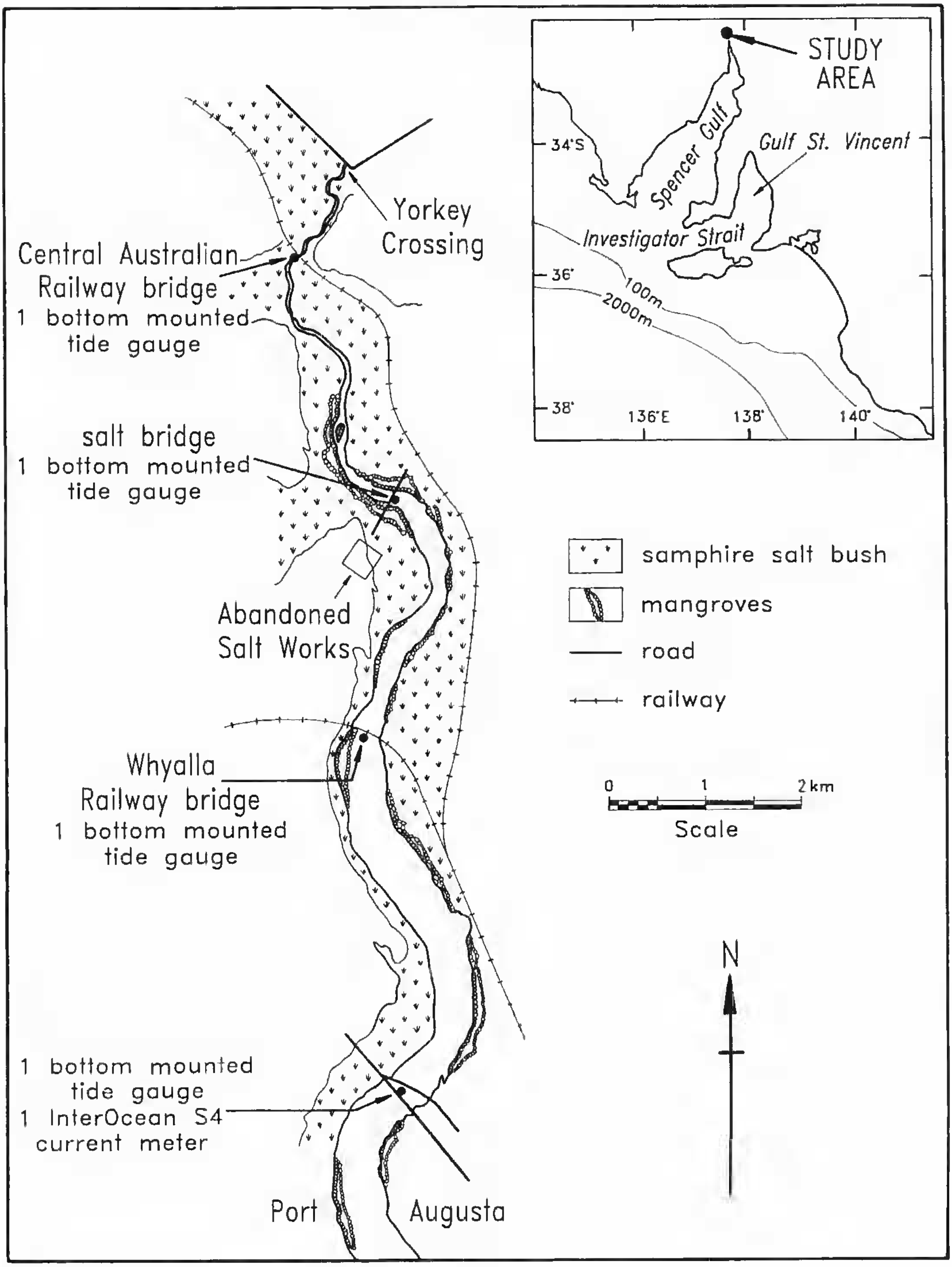

Fig. 1. Locality map of upper Spencer Gulf.

Fig. 2. (a). View of the salt bridge looking westward. Note an investigator (Pat Harbison) on the fringe of the mangrove forest, and the abandoned salt works in the background. (b). View looking southward from just before Yorkey Crossing. Note the samphire flats on the western side of the channel, and the Central Australian Railway bridge in the background. Both views were taken a short time after low water.

TABLE 1. *Tidal constituents for the upper Spencer Gulf.*
a = amplitude; g = phase in degrees. The tidal elevations are in mm and the currents are in cm/s. Currents are related to the magnetic bearing. The record lengths used with the analysis are given in the text.

	Elevations								Currents			
Constituent	Port Augusta (1986)		Whyalla Railway bridge		salt bridge (1986)		Central Aust Railway bridge		Port Augusta (East)		Port Augusta (North)	
	a	g	a	g	a	g	a	g	a	g	a	g
O_1	248	39	265	42	263	51	149	75	0.75	322	2.98	337
K_1	453	73	462	74	451	80	308	90	0.68	1	2.14	4
M_2	617	206	611	210	559	223	245	227	2.14	140	9.28	139
S_2	644	257	704	267	680	275	301	288	2.62	198	10.8	202
$3M_2S_2$	44	68	24	15	5	278	35	19	0.18	63	0.58	109
Mu_2	138	224	121	300	92	310	33	289	0.28	218	1.15	274
$2SM_2$	149	93	107	76	111	121	33	21	0.52	52	2.45	57
$3S_2M_2$	42	165	13	18	31	175	26	85	0.19	347	0.42	350
MO_3	9	91	17	63	10	175	28	284	0.03	79	1.38	172
SO_3	38	231	41	200	61	242	59	356	0.45	200	3.15	219
SK_3	3	194	13	208	28	359	76	358	0.18	337	1.11	276
M_4	12	325	3	317	29	57	50	132	0.25	59	1.18	18
MS_4	34	9	12	295	77	104	136	138	0.29	142	1.41	32
S_4	11	302	16	323	53	173	78	185	0.45	276	0.54	307
$4MS_6$	3	229	4	345	7	48	1	337	0.05	71	0.37	39
M_6	10	9	9	352	5	129	10	64	0.13	355	0.26	349
$2MS_6$	8	40	14	28	22	149	21	44	0.17	79	0.46	45
$2SM_6$	18	139	11	93	44	211	14	76	0.26	168	1.63	169
S_6	2	286	9	130	21	285	4	265	0.13	36	0.39	27
$4SM_6$	4	242	6	35	4	308	4	14	0.17	202	0.56	221

predicted harmonic series and the residual signal, i.e.

$$\zeta_{Obs}(t) = \zeta_{Pred}(t) + \zeta_{Res}(t)$$

where $\zeta_{Obs}(t)$ is the observed tidal elevation or current, $\zeta_{Pred}(t)$ is the predicted tidal elevation or current, $\zeta_{Res}(t)$ is the difference between the observed and predicted tidal elevation and current.

The predicted harmonic amplitude is given by

$$\zeta_{Pred}(t) = \sum_{i=1}^{n} a_i cos(\sigma_i t - g_i)$$

where a_i is the amplitude of the ith constituent, σ_i is the frequency of the ith constituent, t is the local time of the data and g_i is the corresponding phase lag.

The residual signal includes all tidal frequencies which are not harmonically analysed as well as atmospheric storm surges. These storm surges usually persist for 2 to 4 days depending on atmospheric conditions.

The harmonic analysis of all tidal constituents (Table 1) utilising programs developed by the National Tidal Facility shows the important aspects of the upper Spencer Gulf tide.

Results

The four major primary constituents (M_2, S_2, K_1, and O_1) are the main energy source for the region, and the interactions of the dominant semi-diurnal doublet (M_2 and S_2) generate suites of quarter-diurnal (M_4, MS_4, S_4), frictional semi-diurnal ($3M_2S_2$, μ_2[2], $2SM_2$ and $3S_2M_2$) and frictional sixth-diurnal ($4MS_6$, M_6, $2MS_6$, $2SM_6$, S_6, and $4SM_6$) shallow water constituents (Pugh 1987). Terdiurnal (MO_3, SO_3, and SK_3) shallow water constituents are also generated through interactions between the four major primary constituents. The MK_3 constituent, however, is not resolvable from the SO_3 constituent owing to the short length of our records. The tidal energy spectrum at the Central Australian Railway bridge (Fig. 3) clearly shows energy peaks for each of these bands, and also that this energy is resolved by the harmonic analysis. Two prominent higher frequency bands not presented in Table 1, are also shown.

Table 1 indicates that the primary constituents have a maximum amplitude between the Whyalla Railway bridge and the salt bridge and also that their phases increase between Port Augusta and the Central Australian Railway bridge. At Port Augusta the tidal currents lead the tidal elevation by about 60°, indicating a northwards propagation of energy.

Each group of the shallow water constituents appears to behave differently, although there is large variability between the constituents within the groups. The

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[2] Only part of μ_2 is a shallow water constituent, μ_2 also is a minor primary tide.

clearest signal is shown by the quarter-diurnal constituents, the amplitudes of which are far greater at the Central Australian Railway bridge. The amplitudes are approximately in the ratio of 1:2:1 for most stations in agreement with theoretical prediction (Gallagher & Munk 1971) and differ by about 180° between Port Augusta and the salt bridge (Table 1). This is consistent with a node occurring near the Whyalla Railway bridge where the quarter-diurnal amplitudes are a maximum. The phase of the terdiurnal constituents also differs by about 180° between Port Augusta and the Central Australian Railway bridge where the amplitudes are about half of the quarter-diurnal amplitudes.

The frictional sixth-diurnal constituents, on the other hand, tend to have maximum amplitudes at the salt bridge and very variable phases. Finally, the frictional semi-diurnal constituents show maximum amplitudes at Port Augusta, with the suggestion of secondary maxima at the salt bridge.

Discussion

The propagation of the primary tidal constituents (and also the frictional semi-diurnal shallow water constituents) into upper Spencer Gulf gives rise to the most vigorous tide in South Australia which occurs between the Whyalla Railway bridge and the salt bridge where there is a generation of frictional shallow water tidal energy. The position of this maximum tide coincides approximately with the node of the quarter-diurnal tide. The maximum tidal range is defined as the summation of the mean spring semi-diurnal range (MSR) and the mean spring diurnal range (MDR) where MSR = 2 (M_2 + S_2) and MDR = 2 (K_1 + O_1) (Easton 1978). Following the above definition the maximum recorded tidal range for South Australian waters occurs at the Whyalla Railway bridge and corresponds to an elevation of 4.1 m, compared to the range at Port Augusta of 3.9 m. This tidal range identifies the tide as being at the very upper end of the mesotidal range (2.1 - 4.2 m).

Friedrichs and Aubrey (1988) have classified estuaries in which the lunar semi-diurnal tide (M_2) is dominant over the solar semi-diurnal tide (S_2) into ebb dominant and flood dominant. In an ebb dominant estuary, much greater tidal currents occur during the ebb following the exposure of mudflats and the release of intertidal storage. To overcome these effects the duration of the ebb tide is far less than the flood tide. The consequence of ebb dominance is to provide a mechanism for the long-term outwelling of sediments and pollution. In the reverse situation of flood dominance, the estuary usually does not contain intertidal mudflats and thus the duration of the flood tide is less than the ebb and as a result the currents are greater on the flood tide. Flood dominant estuaries

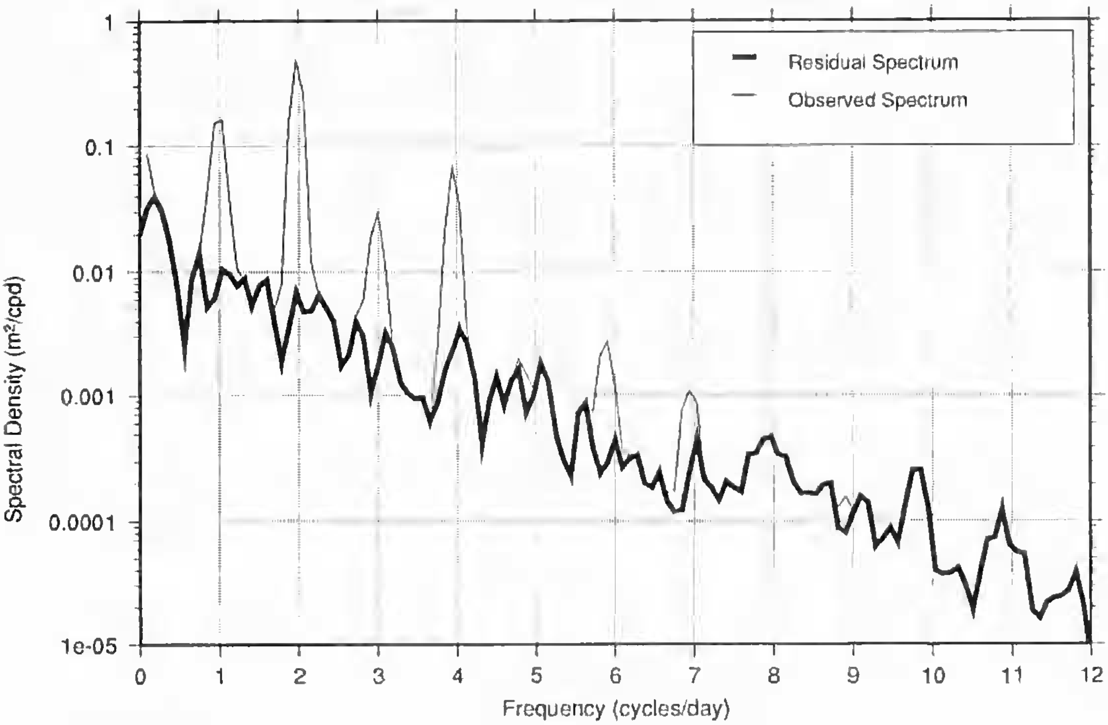

Fig. 3. Power spectrum of tidal energy at the Central Australian Railway bridge.

usually consist of more unstable geometries and in the long term become filled with fine sediments which arise from the net transport into the estuary. This classification is based on the phase difference between the primary lunar tides (M_2) and the major shallow water tide (M_4). In the ebb dominant situation the minimum M_4 current approximately coincides with the maximum of the M_2 current, and in the flood dominant situation the maximum of the M_4 current approximately coincides with the maximum of the M_2 current.

We find that this classification is not appropriate for the brine estuary of upper Spencer Gulf, which behaves either as high water or low water dominant. High water dominant conditions occur when the differences between the high water level and mean sea level are much greater than those between the low water level and mean sea level; the opposite occurs for low water dominant conditions. In high water dominant situations the maximum of the dominant shallow water constituent approximately coincides with the maximum of the primary tidal amplitude and vice versa. For example, at the Central Australian Railway bridge, the phase difference between the MS_4 constituent and its corresponding astronomical generating tide is (M_2+S_2)-$MS_4 = 17°$.

The high water dominant environment consists of a well defined channel which is very shallow at low water, but which can accommodate the propagation of the incoming and outgoing tides except very near high water when overbank flow on the samphire banks occurs. However, with the low water dominant environment, the channel is deep enough to have a negligible effect on low water levels, but as high tide approaches, large volumes of water spill into the adjacent mangrove areas filling up the intertidal depressions and truncating the high water level. The node between these two environments where the most vigorous tide occurs marks the position where these two opposite effects are in balance. These properties appear to be due to the almost equal amplitudes of M_2 and S_2 (see below).

High water dominant conditions are well developed at the Central Australian Railway bridge such that the low water levels appear to be "cut-off" (Fig. 4b). There are four interesting features of this record. First, the low water levels at the neap tide are lower than at the spring tide. It is believed that this is the result of the formation of intertidal pools of gulf water trapped between the Central Australian Railway bridge and Yorkey Crossing. Water is held in this region on the ebbing tide which is slowly drained until the tide turns but during the neap cycle, less water is able to be stored in the upper reaches and subsequently the low water level is less than the spring tidal level.

Second, the diurnal inequality of the tide produced by the beating of the diurnal and semi-diurnal constituents is significantly modulated at the Central Australian Railway bridge relative to the Whyalla Railway bridge due to the generation of the terdiurnal tides.

Third, the residual records show that storm surges are usually greatly attenuated between Whyalla and Central Australian Railway bridges.

Fourth, the drainage from the samphire flats retards the low tide much more than the high tide. The approximate lags between Yorkey Crossing and Port Augusta, determined directly from the short tidal records of the pilot study, were high water 35 min, low water 180 min. Similar results can be obtained from Fig. 4a and b. The difference between the lags is primarily due to the major quarter diurnal shallow water tide (MS_4), as can be seen from Fig. 5a in which the three tidal constituents M_2, S_2 and MS_4 are represented as well as the combination of the three. An interesting feature of Fig. 4b is the form of the tidal range curve during the ebb, which resembles an exponential drainage curve, and is clearly reproduced in Fig. 5a. Thus the drainage from the samphire flats is explained harmonically by the existence of MS_4. This appears to be a unique property of the system in which M_2 and S_2 have approximately the same amplitude. The corresponding current record (Fig. 5b), which is constructed by differentiating the tidal elevations with respect to time, and scaling to give maximum tidal velocities similar to the observations (~ 0.35 ms^{-1}) shows characteristic current spikes at the beginning of both the ebb and flood tides which are of similar amplitude and also a slow ebb (~ 3 cms^{-1}) during low tide. This structure was observed in the short period current meter deployments just south of Yorkey Crossing and at the salt bridge (Bye & Harbison 1987, 1994).

Flattening of high water can be seen in the Whyalla Railway bridge record (Fig. 4a) but the importance of MS_4 (Table 1) is much smaller here than in the high tide dominant conditions at the Central Australian Railway bridge.

Conclusions

Following an extensive field programme of tidal elevations and currents, the largest tide in South Australia is believed to exist in upper Spencer Gulf, north of Port Augusta. This tide is the peak of the three-quarter resonance in Spencer Gulf which gives rise to a rapid increase in amplitude northwards from near Wallaroo. The location of the Whyalla Railway bridge was observed to have the largest amplitudes of the major astronomical tidal constituents (namely the M_2, S_2, K_1 and O_1 tides) giving a tidal range which lies within 4 to 4.5 m where typically the tidal range in both gulfs is closer to 2.5 to 3 m. Just beyond the bridge

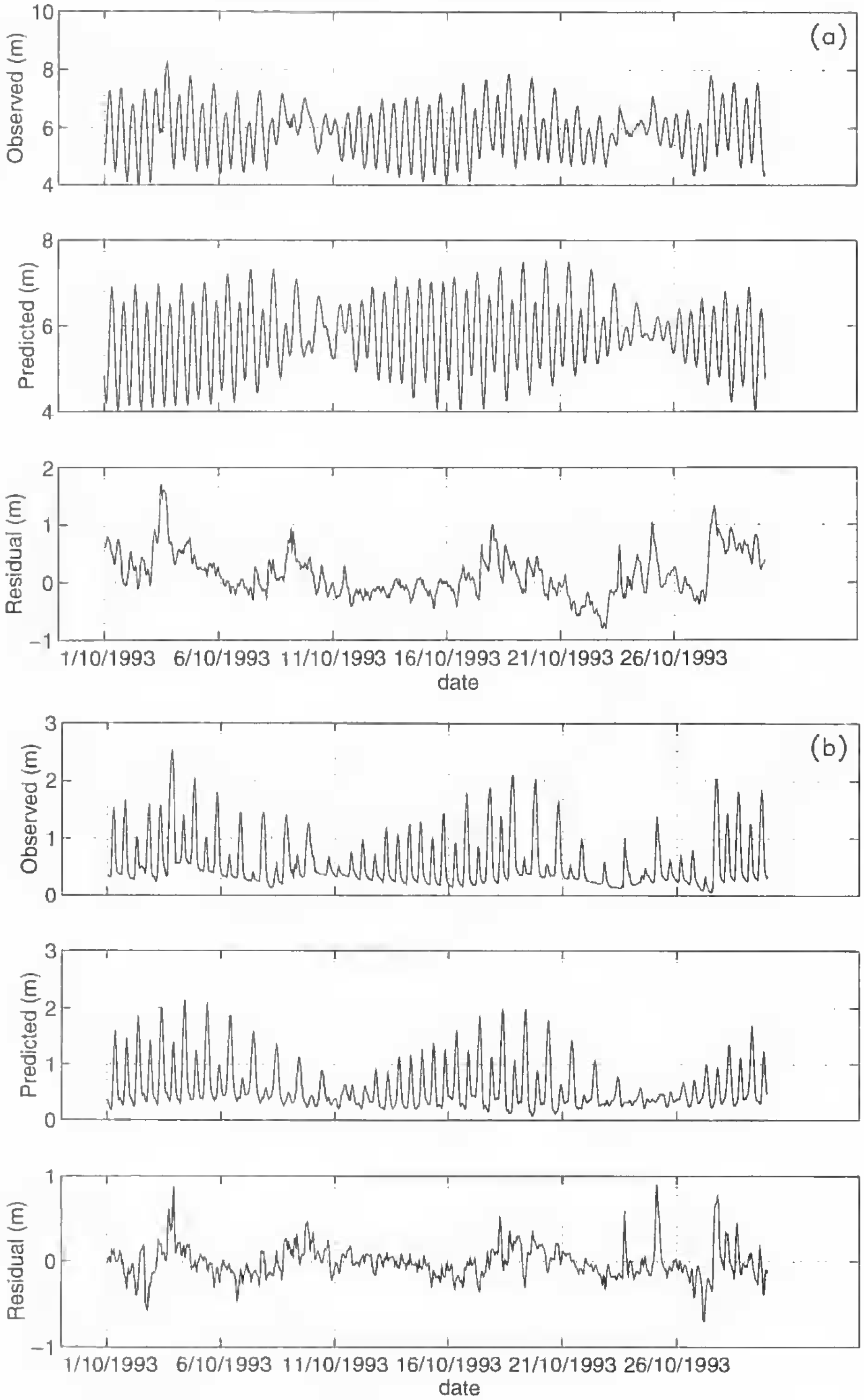

Fig. 4. Tidal observations for October 1993. (a). The Whyalla Railway bridge. (b) The Central Australian Railway bridge. The residual (Res) = the observed (Obs) - the predicted (Pred) tidal elevation.

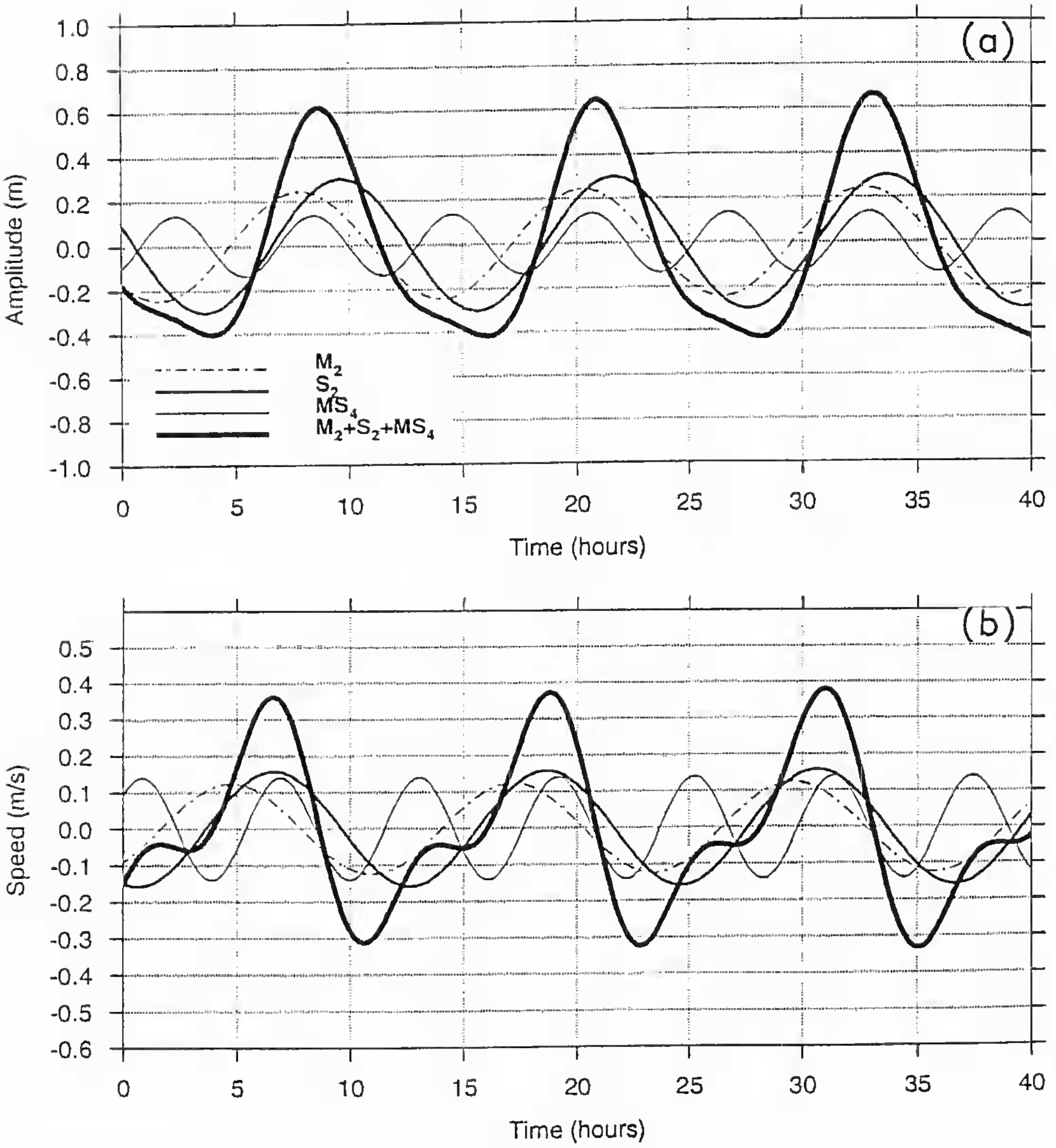

Fig. 5. (a) Tidal elevations and (b) Tidal currents at the Central Australian Railway bridge, constructed using the tidal constituents M_2, S_2, and MS_4.

a shallow water tidal node occurs and we identify this location as the probable position of the largest tidal range. As in all tidal studies, however, the longer the length of tidal records, the better is the harmonic analysis. In this study we have relied on one-two month deployments at several locations. Longer records would be necessary to improve the accuracy of the tidal constants.

The nonlinear interaction between the major astronomical constituents and the surrounding bathymetric features leads to the generation of significant shallow water tides, especially the quarter diurnal MS$_4$ constituent which dominates because of the similar amplitudes of the M$_2$ and S$_2$ tides.

These observations prompt the speculation that the samphire flats and mangrove forest environment have evolved as a positive feedback to the shallow water tidal interactions. In other words, in the absence of the unusual South Australian tidal regime in which the major semi-diurnal tidal constituents (M$_2$ and S$_2$) have a similar amplitude, the intertidal environment would be quite different.

It is also likely that the changes in the intertidal environment of upper Spencer Gulf and its northward extension into the Pirie-Torrens plains that have occurred due to sea level changes have been decisively influenced by shallow water tidal interactions.

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